Spin-Dependent Quantum and Transport Lifetimes in a Two Dimensional Electron or Hole Gas in the Presence of Rashba Effect

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At present, one important aspect in the field of spin-electronics (or spintronics) is to investigate spin polarized electronic systems realized from semiconductor quantum well structures in the absence of an external magnetic field, due to important applications to novel electronic devices such as spin-transistor, spin-waveguide, spin-filter, quantum computer, etc. It is known that in semiconductor-based two-dimensional electron or hole gas (2DEG or 2DHG) systems, the zero-magnetic-field spin splitting can be realized from inhomogeneous surface electric field induced by the presence of the heterojunction. This feature is known as the Rashba effect. The state-of-the-art material engineering and micro- and nano-fabrication techniques have made it possible to achieve experimentally observable Rashba effect in, e.g., InGaAs-based 2DEG [1] and GaAs-based 2DHG [2] systems. In these novel device systems, the Rashba spin-splitting and the corresponding spin orbit interaction (SOI) can be controlled by applying a gate voltage or varying sample growth parameters.

In recent years, the effect of the SOI on electronic and transport properties of 2DEGs and 2DHGs has been intensively studied. At present, one of the most powerful and most popularly used experimental methods to identify the Rashba spin splitting is magneto-transport measurements carried out at quantizing magnetic fields and low temperatures at which the Shubnikov-de Hass (SdH) oscillations are observable. From the periodicity, amplitude, and profile of the SdH oscillations, the density and quantum lifetime in different spin branches, together with the Rashba parameter, can be determined experimentally. It has been observed experimentally [1] that in InAs-based spintronic systems, although electron densities in different spin branches can differ significantly, the quantum lifetimes depend very weakly on the strength of the SOI. In order to understand this important and interesting experimental finding, here we present a tractable theoretical approach to examine quantum and transport lifetimes pertinent to a 2DEG or a 2DHG.

Using a momentum-balance equation approach on the basis of a semiclassic Boltzmann equation, the transport and quantum lifetimes (τ_t^σ and τ_q^σ) in different spin branches can be calculated, respectively, by

$$n_\sigma = \sum_{\sigma'} [\tau_t^\sigma B_{\sigma'\sigma} - \tau_t^{\sigma'} C_{\sigma\sigma'}] \tag{1}$$

and

$$\frac{1}{\tau_q^\sigma} = \frac{1}{n_\sigma} \sum_{\sigma'} B_{\sigma'\sigma}. \tag{2}$$

Here, $\sigma = \pm 1$ refers to different spin branches, n_σ is electron or hole density in the spin branch σ, and $B_{\sigma'\sigma}$ and $C_{\sigma\sigma'}$ are induced by electronic transitions in different spin orbits due to electron or hole interactions with scattering centers. In this work, we consider electron or hole interactions with background impurities via screened Coulomb or short-range δ-function potential in a high-mobility 2DEG or 2DHG system. We have studied the dependence of the quantum and transport lifetimes on strength of the SOI in InGaAs-based 2DEG and GaAs-based 2DHG systems, using typical sample parameters for these structures.

We find that: (1) in the presence of SOI, transport lifetime in the $\pm$ spin branches differs significantly in both 2DEG and 2DHG; (2) a more pronounced difference between τ_t^+ and τ_t^- can be observed at a larger Rashba parameter; and (3) τ_t^σ induced by electron-impurity via a screened Coulomb potential is roughly the same as that via a short-range δ-function potential. In contrast, (i) over a wide range of the Rashba parameter, quantum lifetime in different spin branches depends very weakly on SOI in a 2DEG or a 2DHG; (ii) a very large Rashba parameter is required to separate τ_q^+ and τ_q^-; and (iii) τ_q^σ depends strongly on the form of the electron-impurity scattering potential.

Our theoretical results indicate that a rather small difference between τ_q^+ and τ_q^-, observed also experimentally in an InAs-based 2DEG [1], is mainly due to unique features of electronic scattering in the presence of SOI. When the SOI is present, the energy dispersion of a 2DEG or a 2DHG is no longer parabolic and the energy levels of different spin branches depend strongly on k (wavevector or momentum of an electron). In such a case, the spin orientation can change continuously with the momentum orientation when an electron or hole moves in $\mathbf{k}$-space. Thus, the SOI can shift $\pm$ branch of the spectrum continuously in $\mathbf{k}$-space instead of a quantized spectrum in energy space for a usual case. As a result, electrons or holes are able to change their spin orientation simply through momentum exchange which can be more easily achieved than that through energy exchange for a usual case. These features are very favorable for separating transport lifetimes τ_t^+ and τ_t^-. However, an elastic and small-angle scattering in a 2DEG or a 2DHG cannot change significantly the spin orientation of the conducting carriers, because it requires only a small momentum and energy exchange during a scattering event. On the basis that a quantum lifetime (determined experimentally from the SdH oscillations via the Dingle plot) measures the strength of the small-angle scattering, a small difference between τ_q^+ and τ_q^- can be understood.

One important conclusion drawn from this study is that in spintronic systems such as spin-split 2DEG and 2DHG induced by Rashba effect, small-angle scattering cannot alter significantly the spin orientation of the carriers. To achieve a large exchange of the spin orientation through electronic scattering in these systems, inelastic and/or large-angle electronic transitions have to be involved. This result is useful in designing spintronic devices. Moreover, although the energy spectrum for a spin-split 2DEG (linear-in-k term) differs essentially from that for a 2DHG (k^3 term), we expect that a rather small difference of the quantum lifetime in different spin branches can also be observed in a 2DHG system.

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